High-p_T at RHIC

BNL, March 17, 2010

George Sterman, Stony Brook

- Mostly jets today, but hopefully with implications for heavy quarks and spin

I. Jets of our choice: energy flow

II. Some comments on jet finding and algorithms

III. Single particle cross sections and a recent surprise

I. Jets of our choice: energy flow

How we use asymptotic freedom

- Infrared safety & asymptotic freedom:

$$Q^2\ \hat{\sigma}_{\rm SD}(Q^2, \mu^2, \alpha_s(\mu)) = \sum_n c_n(Q^2/\mu^2)\ {\alpha_s}^n(\mu) + \mathcal{O}\left(\frac{1}{Q^p}\right)$$
$$= \sum_n c_n(1)\ {\alpha_s}^n(Q) + \mathcal{O}\left(\frac{1}{Q^p}\right)$$

- $\mathrm{e}^+\mathrm{e}^-$ **total; jets**: a sum over collinear rearrangements and soft emission organizes all long-time transitions, which must sum to ≤ 1 by unitarity.

- What we're really looking at here (with local source J)

$$\sigma[f] = \lim_{R\to\infty} \int d^4x \mathrm{e}^{-iq\cdot y} \prod_a \int d\hat{n}^{(a)}\, f_a(\hat{n}^{(a)})$$

$$\times \langle 0|\, J(0) T[\prod_a \hat{n}_i^{(a)} T_{0i}(x_0, R\hat{n}_a) J(y)]\, |0\rangle$$

(Sveshnikov & Tkachov 95, Korchemsky, Oderda & GS 96, Bauer, Fleming, Lee & GS 08, Hofman & Maldacena 08)

With T_{0i} the energy momentum tensor at the detector

- "Weights" $f^{(a)}(\hat{n})$ should introduce no new dimensional scale

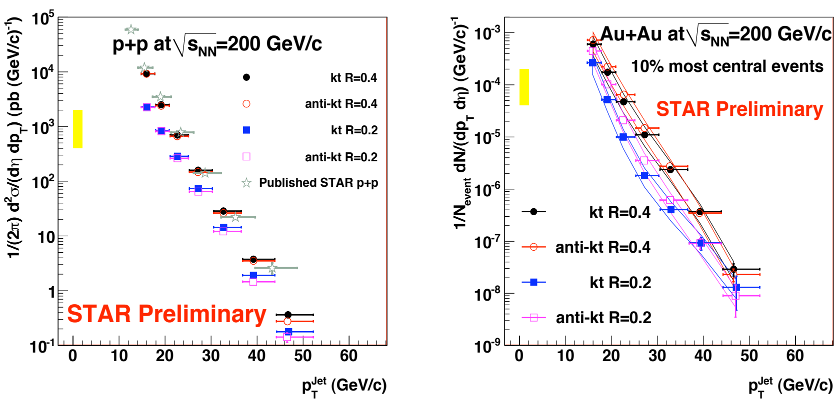
Short-distance dominated if all f continuous almost everywhere.

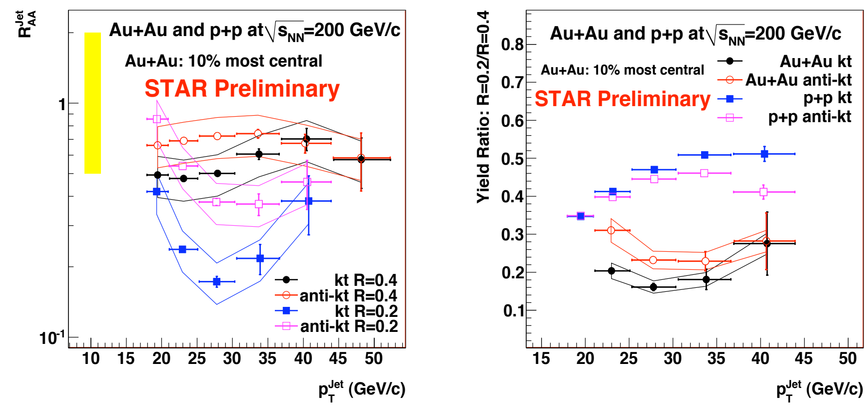
- We only have to ask "smooth" questions.

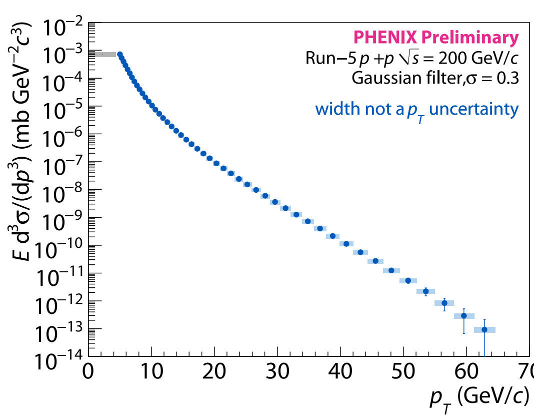
II. A few comments on algorithms

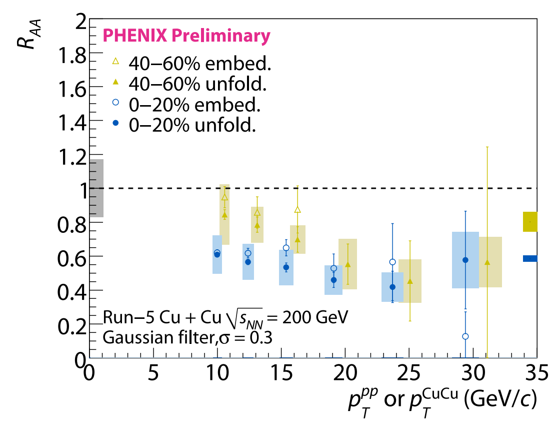
The basic observation: different jet definitions give different answers, but we can understand (ideally compute) differences between different jet definitions.

RHIC jet finding has become sophisticated & inventive. I'd just like to make a few comments on cone, anti-kt and Gaussian filter algorithms.


p+p at $\sqrt{s_{NN}}$=200 GeV/c
kt R=0.4
anti-kt R=0.4
kt R=0.2
anti-kt R=0.2
Published STAR p+p
STAR Preliminary
1/(2π) d²σ/(dη dp_T) (pb (GeV/c)⁻¹)
p_T^Jet (GeV/c)
Au+Au at $\sqrt{s_{NN}}$=200 GeV/c
10% most central events
STAR Preliminary
kt R=0.4
anti-kt R=0.4
kt R=0.2
anti-kt R=0.2
1/N_event dN/(dp_T dη) (GeV/c)⁻¹
p_T^Jet (GeV/c)


Au+Au and p+p at $\sqrt{s_{NN}}$=200 GeV/c
Au+Au: 10% most central
STAR Preliminary
kt R=0.4
anti-kt R=0.4
kt R=0.2
anti-kt R=0.2
R_AA^Jet
p_T^Jet (GeV/c)
Au+Au and p+p at $\sqrt{s_{NN}}$=200 GeV/c
Au+Au: 10% most central
STAR Preliminary
Au+Au kt
Au+Au anti-kt
p+p kt
p+p anti-kt
Yield Ratio: R=0.2/R=0.4
p_T^Jet (GeV/c)


PHENIX Preliminary
Run–5 p+p $\sqrt{s}$ = 200 GeV/c
Gaussian filter, σ = 0.3
width not a p_T uncertainty
E d³σ/(dp³) (mb GeV⁻²c³)
p_T (GeV/c)


PHENIX Preliminary
40–60% embed.
40–60% unfold.
0–20% embed.
0–20% unfold.
Run–5 Cu + Cu $\sqrt{s_{NN}}$ = 200 GeV
Gaussian filter, σ = 0.3
R_AA
p_T^pp or p_T^CuCu (GeV/c)

Cone algorithms

- Cones: Relatively straightforward if you're looking for one jet inclusive, but cones can't stay rigid, they overlap in general and must be "split or merged."
- First step is time consuming: identifying cones centered on total momenta of the enclosed particles (stable cones.)
- Intuitive basis: cone size as an "angular resolution" for collinear splitting analogous to the "energy resolution" infrared massless photons in QED.
- Large cones are subject to large fluctuations from backgrounds, especially in central AA collisions.
- The weight functions are θ functions: not so smooth but still "IRC" finite.

Recombination algorithms

– Successively combine pairs of "objects". The most familiar are k_T algorithms, generalized by Salam, Cacciari, Soyez:

$$d_{ij} = \min\left(k_{iT}^{2p}, k_{jT}^{2p}\right) \frac{\Delta R_{ij}}{R}, \quad 1 \geq p \geq -1$$

Generally, combine the smallest pairs d_{ij} into new objects.

– $p = 1$ is the k_T algorithm: the softest particles are clustered first, hard particles last. Generally irregular.

– Irregularity may reflect quantum mechanical fluctuations in gluon emission, so not necessarily a disadvantage.

– Combinatorics of pairs is simpler than the problem of identifying stable cones.

The anti-k_t option

$$d_{ij} = \min\left(k_{iT}^{-2}, k_{jT}^{-2}\right) \frac{\Delta R_{ij}}{R}$$

– $p = -1$ is the anti-k_T algorithm: clustering dominated by hard particles. Generally regular.

– Combines the efficiency of k_T with intuitive appeal of cones.

– Relation to energy flow remains implicit, and analysis of nonperturbative effects is so far mostly by comparison to event generators.

Gaussian filtering.

(Lai and Cole, 2008)

– Seems to me most closely to energy flow, with a weight function as above.

– Replaces the θ-function weights of cone algorithms with a truly smooth function.

$$\tilde{p}_T(\eta,\phi) = \int d\hat{n}\, p_T(\hat{n})\, e^{-(\eta-\eta(\hat{n}))^2-(\phi-\phi(\hat{n}))^2}$$

which is

$$\tilde{p}_T(\eta,\phi) = \lim_{R\to\infty} \int d\hat{n}\, \frac{1}{\cosh\eta(n)} \langle AA|\hat{n}_i T_{0i}(x_0, R\hat{n})\,|AA\rangle \times e^{-(\eta-\eta(\hat{n}))^2-(\phi-\phi(\hat{n}))^2}$$

- **The jets are found afterwards by identifying local maxima.**

  from Lai, 2009

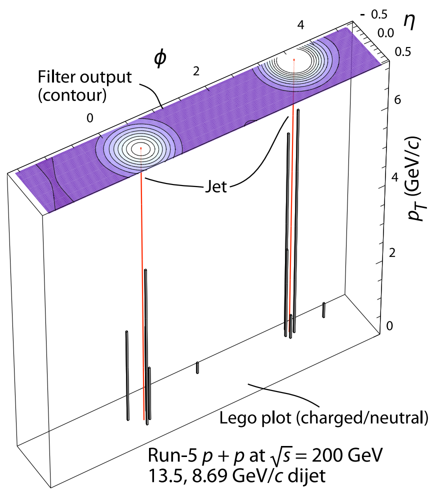


Figure 1: A PHENIX Run-5 $p+p$ at $\sqrt{s} = 200\,\mathrm{GeV}$ dijet event. Charged tracks and photons are shown at the bottom by a Lego plot. The distribution of filter output values of the event is shown at the top as a contour plot. The maxima in the filter density are reconstructed as jet axes, shown as red lines at the positions on the contour and Lego plots.

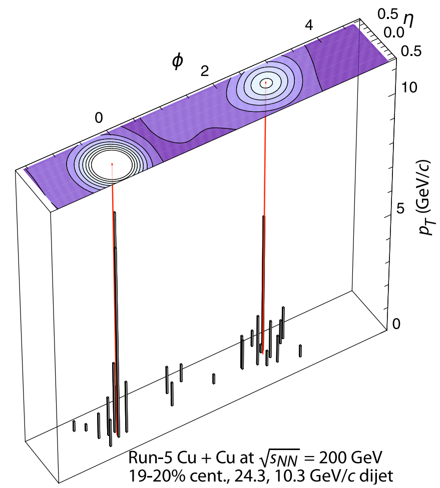


Figure 2: A PHENIX Run-5 Cu + Cu at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ dijet event at $\approx 20\%$ centrality. Charged tracks and photons are shown at the bottom by a Lego plot. The distribution of filter output values of the event is shown at the top as a contour plot. The maxima in the filter density are reconstructed as jet axes, shown as red lines at the positions on the contour and Lego plots.

- **Energy correlations could shed light on jet interactions in media: ridges, shock waves . . .**

III. Single particle cross sections

$$Q^2\sigma_{\rm phys}(Q,m,f) = \omega_{\rm SD}(Q/\mu,\alpha_s(\mu),f) \otimes \phi_{\rm LD}(\mu,m) + \mathcal{O}\left(\frac{1}{Q^p}\right)$$

μ = factorization scale;
m= IR scale **(m *may* be perturbative)**

- **"New physics" in $\omega_{\rm SD}$; $f_{\rm LD}$ "universal"**
  – think of "$x_T = 2p_T/\sqrt{s}$ scaling." For single-particle cross section, use $\phi_{LD} = D(z)$, fragmentation functions.

- **Almost all collider applications. Enables us to compute the Energy-transfer-dependence in $|\langle Q,\ {\rm out}|A+B,\ {\rm in}\rangle|^2$.**

Evolution

- **Whenever there is factorization, there is evolution**

$$0 = \mu \frac{d}{d\mu} \ln \sigma_{\rm phys}(Q,m)$$

$$\mu \frac{d \ln f}{d\mu} = -P(\alpha_s(\mu)) = -\mu \frac{d \ln \omega}{d\mu}$$

- **Wherever there is evolution there is resummation,**

$$\sigma_{\rm phys}(Q,m) = \sigma_{\rm phys}(q,m)\ \exp\left\{ \int_q^Q \frac{d\mu'}{\mu'} P\left(\alpha_s(\mu')\right) \right\}$$

- **For example:** $\sigma_{\rm phys} = E \frac{d\sigma}{d^3p}$, **single-particle inclusive.**

- **Fragmentation functions are results of "global" analyses (including recently, DSS, AKK . . .), from LEP, RHIC, HERA, Tevatron data.**
- **Works pretty well, even in sophisticated cases like dihadrons when full evolution and resummation is taken into account**

  (Almeida, GS, Vogelsang (2009))

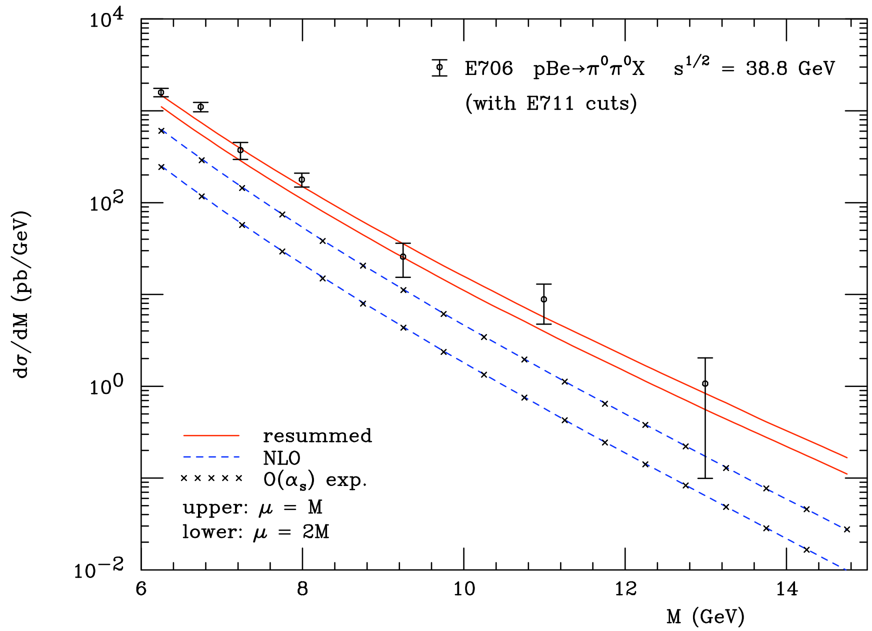
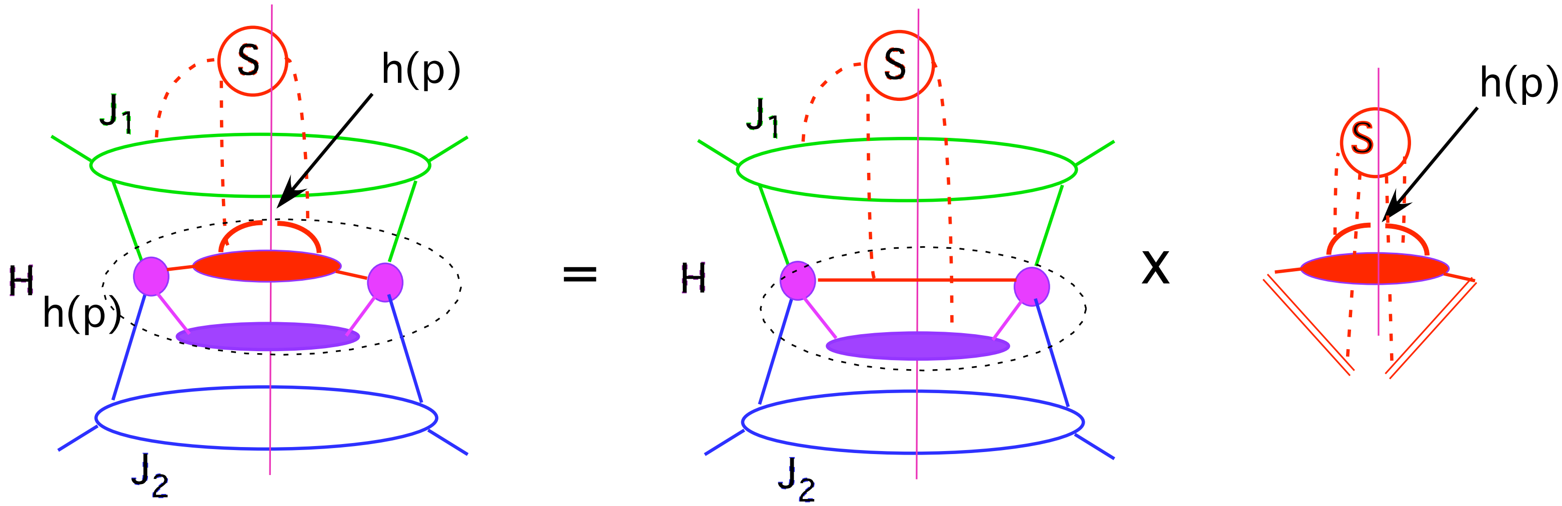


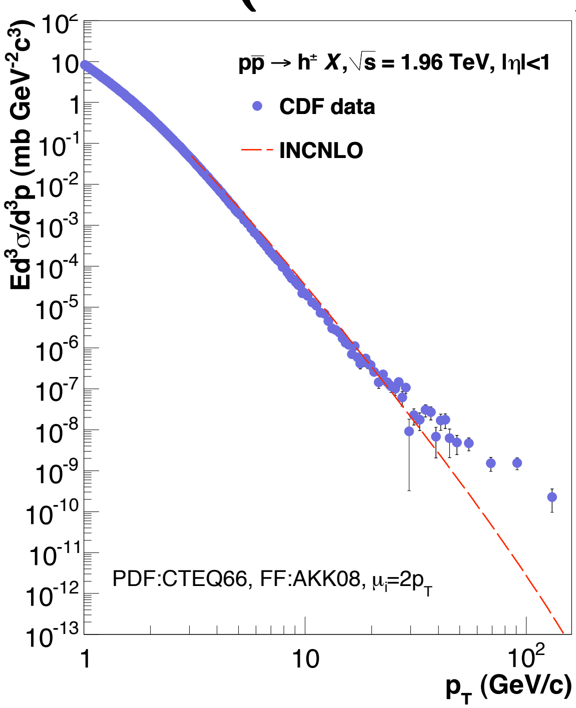
Figure 6: *Comparison to E706 data with a different set of cuts, corresponding to the ones applied by E711. The data with these cuts are from [11].*

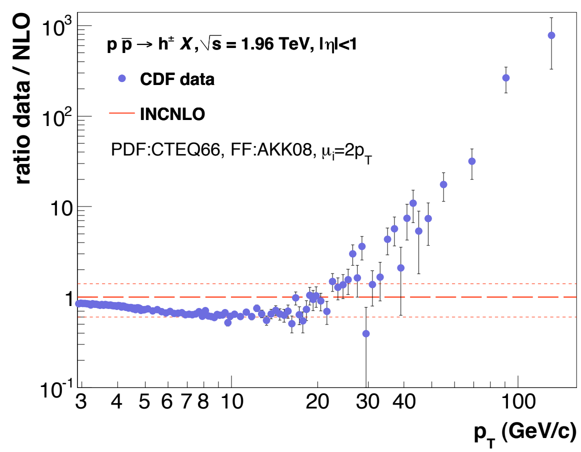
- **And the theory is pretty well-understood:**
- **The schematic proof of factorization for fragmentation:**



- **Known corrections lead to energy loss and more radiation – as seen in central AA.**
  At moderate p_T higher-power corrections to 1PI can be important. **(Arleo, Brodsky, Huang & Sickles (0911.4604))**
- **Imagine, then, our surprise with this 1PI unidentified charged hadron data . . .**

- **Year-old CDF Data, as analyzed in papers by Albino, Kniehl and Kramer (1003.1954) Arleo, d'Enteria and Yoon (1003.2963):**

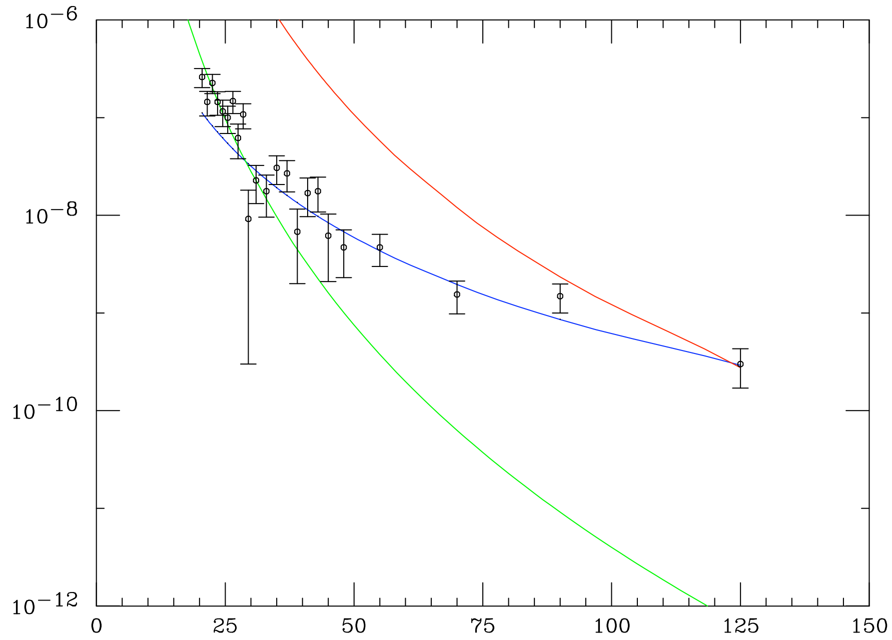




- **This data had been hanging around since last April (0904.1098), but its significance was lost in a comparison with PYTHIA tunes. It was published in Phys. Rev. D (2009).**
- **Both AKK and AEY observe: either a (big) problem with universality of fragmentation or with the data itself.**

- **A QCD description is difficult. Isolated single pions are suppressed compared to jets by at least $\alpha_s(f_\pi/p_T)^2 \sim 10^{-4}$ at 100 GeV.**
- **But compared to NLO jets (red) and NLO 1PI (green) the data (with green fit) looks like:**

(Vogelsang, yesterday)



- **At 100 GeV, the single-particle cross section saturates the jet cross section.**
- **This can't go on, because the 1PI cross section is much flatter than the jet cross section, which is confirmed experimentally at much higher p_T!**
- **A problem ... but could this be something new and unexpected?**
- **We've been grasping at this straw over the past couple of days. The next equations are everyone else's credit and my fault, as appropriate ...**
- **For illustrative purposes only!**

- **A general form at $\eta = 0$; $z = x_a x_b = \hat{s}/S$:**

$$E\frac{d^3\sigma}{d^3p_T} = \frac{1}{p_T^4} \int_{x_T^2}^{1} dz \mathcal{L}_{\mathrm{partonic}}(z)\, \omega(x_T, z)$$

- **Suppose a narrow resonance at $M^2 = z_0 S$ decays to single hadrons plus unobservable particles . . .**

$$\omega(x_T, z) = f(4x_T^2/z_0)\, \delta(z - z_0)$$

- **Then**

$$E\frac{d^3\sigma}{d^3p_T} = \frac{1}{p_T^4} \mathcal{L}_{\mathrm{partonic}}(z_0)\, f(4x_T^2/z_0)$$

- **and the distribution $f(4x_T^2/z_0)$ can be read off from the data where it dominates QCD fragmentation, while it cuts off abruptly at $2x_T = \sqrt{z_0}$.**
- **But of course, it should be wide and not narrow, and where does the rest of the energy go, etc., etc?**

- **Conclusions . . . Jets in heavy ions have entered a new era, and multi-energy correlations may be a route to go.**
- **For one-particle inclusive cross sections, we're still catching our breath, but one way or another there is a lot to learn.**